Assessment of Fibre Content and Orientation in SFRC with the Inductive Method. Part 2: Application for the Quality Control of Sprayed Concrete

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Abstract

Concrete is the most used construction material in the world despite its fragility and low capacity to bear tensile stresses. Steel fibres may be added to increase the ductility of the material leading to fibre reinforced concrete (FRC) that is used in many applications, such as sprayed concrete. When concrete is sprayed, fibres are rebounded affecting negatively the mechanical behaviour of the FRC. To control the fibre content a new non-destructive method is presented: The inductive method. The present work compares it with the traditional one and proposes a methodology to control the fibre content of the sprayed fibre reinforced concrete (SFRC).

Keywords: Inductive method, traditional method, fibre reinforced concrete, sprayed concrete, rebound

1. Introduction

The concrete is the most used construction material in the world despite its fragility and low capacity to bear tensile stresses [1]. This material evolved considerably during the last years and special concretes emerged in order to solve the drawbacks of the conventional concrete. In that sense, steel fibres are added into the concrete mixes to increase the ductility of the material entailing a composite called fibre reinforced concrete (FRC) [1, 2].

The fact that fibres are discrete and randomly distributed in the concrete mix leads to a 3-dimensional reinforcing mechanism different from that of conventional reinforced concrete [3]. Even though, as the conventional reinforced concrete mechanical properties are dependent on the quantity of rebars used, the FRC mechanical behaviour depends on the fibre content considered in the mix [1, 2, 3, 4]. Thus, it is important to establish a control methodology to assess the amount of fibres of a FRC.

In the particular case of using FRC for sprayed concrete applications, the control of the fibre content is especially important. When concrete is sprayed, part of the components is rebounded [5, 6, 7]. This affects also the fibres, thus reducing the remaining content at the sprayed layer and affecting negatively the mechanical behaviour of the material [8, 9, 10]. Considering a statistical analysis of the difference between the amount of fibres in the design mix and the one after spraying, engineers may be able to optimize the content of fibres for structural and economic reasons.

To assess the fibre content of the sprayed fibre reinforced concrete (SFRC) the traditional method can be used. This method for estimating the content of fibre in the mixes is time-consuming and difficult to perform in sprayed material. According with the existing procedure, samples must be crushed and the fibres separated and weighted. A human factor may influence the results as all the process depends on the technician.

Furthermore, the traditional method is a destructive test which eliminates the possibility of repeat the test. For the reasons exposed, a non-destructive test, the inductive method, has been used to evaluate the quantity of fibres in the FRC [11,12,13]

The main objectives of the present study are two: comparing the traditional and the inductive methods and propose a methodology control the fibre content of a SFRC design mix based on the inductive method. In order to achieve that, the methodology to calibrate the inductive method considering the type of fibres and the procedure that could be applied during the sprayed concrete quality control is presented. Then, samples are extracted from a dry-mix SFRC used to stabilize a slope in a real construction site located in São Paulo (Brazil). These samples are tested and the results analysed.

2. Methodology

This section presents the experimental program. Firstly, the materials, the reference concrete mix and the spraying procedures are explained due to their relationship with the rebound [6, 7]. Subsequently, the process to obtain the samples and the tests considered are detailed.

2.1. Materials

2.1.1. Cement, water, aggregates and additives

One type of cement was used: CP III 40 RS (Brazilian denomination). This was established considering the project specifications. The CP III 40 RS is a type of cement that entails higher compressive strength than a regular cement due to a high content of blast furnace slag (35-70%). Furthermore, this addition improves concrete workability and pumpability, fundamental aspects of the spraying performance [1].

Potable water following all the requirements defined by the Brazilian standard NBR 15900:2009 [14] was used in the mix. Limestone course and fine aggregates complying with the Brazilian standard NBR 7211:2009 [15] were used. These aggregates were a 0-4 mm sand and a 4-12 mm gravel. These fractions were selected to assure a good workability of the mixes as well as to avoid stroke problems during pumping, to reduce the rebound and to generate an optimal packing of the concrete [5, 16].

Two additives were used: a plasticizer Mastermix BF 10 and a microsilica. Both are typical additives for sprayed concrete. The first one is used to improve the workability of the mixes to facilitate the spraying process [5], whereas the second improve the mechanical properties of the concrete and decreases the rebound [1, 5]

2.1.2. Fibres

A type of fibre was used: Wirand type FSN3, supplied by Maccaferri (Figure 1). This is a fibre recommended for spraying concrete which have a length (L) and a slenderness ratio (L/D) equal to 33 mm and 44, respectively. This geometric and mechanical properties were evaluated based on the Brazilian standard NBR 15530:2007 [17]. Finally, in order to study how the quantity of fibres in the mixes affects the results, five fibre contents were considered: 20, 30, 35, 45 and 55 kg/m^3. These are typical values for spraying concrete [8].

Figure 1- Fibres used: Wirand type FSN3

2.2. Concrete mix

The reference mix used in this study is detailed in Table 1. Notice that the amount of cement used is between 350 and 450 kg/m^3, which is a usual range defined for typical sprayed concrete [16]. The amount of microsilica and plasticizer were 5.0 and 0.25% by cement weight. The water cement ratio adopted was 0.33 which is an acceptable value to spray concrete. The water in the aggregates was taken into account to correct the amount of water added to the mix. Finally, the different fibres contents were applied to the reference mix.

Table 1- Reference mix of sprayed concrete

Material	Dosage
Cement	435.2
Sand 0-4 mm	924.8
Gravel 4-12 mm	809.4
Water	175.2

2.3. Spraying process and obtaining of samples

All mixes were sprayed in the construction site using an only one supplied reference mix. The mixes were sprayed with a dry-mix system following the EFNARC recommendations [16]. In order to do that a compact dry-mix machine, typically used for slope stabilization [15], was used. The mixes were sprayed with a constant air pressure equal to 2.8 kPa on 5 mm-thickness wood test panels. They had an area of 500x500 mm, whereas the height was 125 mm. The position of the test panels, which were collocated on the floor with an angle of 20^o with the vertical [16]. A total of 10 panels were sprayed entailing two test panels for each fibre content considered.

After spraying the test panels, the sprayed concrete pieces were unmoulded at a minimum age of 3 d in order to assure a minimum strength. Next, the concrete pieces were transported from the construction site to the laboratory facilities of the Universidade de São Paulo. There, 5 cores were extracted from each test panels using an extracting machine with a 100 mm diameter drill following the requirements of the European standard UNE-EN 14488-2:2007 [19]. Subsequently, the roughest face of the cores was cut using a radial disc cutting machine. Finally, the samples were sized in order to calculate their volume (V). In that sense, 2 diameters (ϕ) and 2 heights (h) were measured. The sample V was calculated with the average diameter and average heights (h_m and ϕ_m, respectively).

2.4. Tests

Two different tests were considered to assess the fibre content of the SFRC: The traditional and the inductive method. These are presented below.

2.4.1. Traditional method

The simplest way to assess the fibre content of a concrete sample is counting the number of fibres manually. In that sense, crushing the sample ables to separate the fibres to easily determine its content. This methodology follows the requirements of the European standard UNE-EN 14721:2006+A1 [20].

The main drawback of this methodology is that the sample must be crushed and, therefore, the repetitively of the results is not allowed. Furthermore, this method is affected by a human factor, as it depends on the expertise of the technician who performs the test. However, the costs related to the method are really low as the facilities needed are found in all laboratories: a concrete crushing machine, a magnet to collect the fibres and a scale to weight them.

In this study, 10 samples, one for each sprayed test panel were crushed in order to assess their real fibre content. The test lasted 15 min for each sample.

2.4.2. Inductive method

The inductive method (Figure 2.a) tries to eliminate the drawbacks of the traditional method. It is a non-destructive test that uses an electrical coil and its electromagnetic properties in order to estimate the quantity of the fibres in concrete. The methodology was developed by researchers of the Universitat Politècnica de Catalunya [11,12,13]. Its basic concept is that placing a FRC sample in the middle of an electromagnetic field a variation of the inductance (ΔL) is observed. Then placing the sample into the coil in different positions, different ΔL are obtained. Analysing the sum of them (ΔL_T) the fibre content is estimated. In order to do that, a previous calibration of the method must be done regarding the type of fibre used.

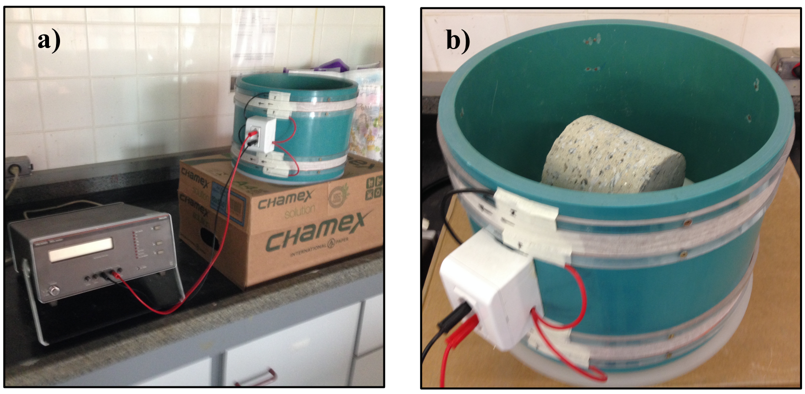

Figure 2- Inductive method equipment a) and sample being tested b)

The performance of the inductive method depends on the shape of the sample [9]. In case of cylindrical samples ΔL_T is obtained considering 4 ΔL readings in different positions: the vertical one (ΔL_z), and three horizontal positions considering three different angle: 0, 45 and 90^o (ΔL_0, ΔL_{45} and ΔL_{90}, respectively) (Figure 2.b). The 50 samples obtained were evaluated entailing 200 ΔL readings. The method, once calibrated, lasted 2 min for each sample entailing a significant reduction of time consumed compared with the traditional method. Notice that the inductive method is widely explained in [21].

3. Results and analyses

This section presents the results and their analysis. Firstly, the inductive method is calibrated. Then, it is compared with results obtained with the traditional method. Subsequently, the inductive method is used to estimate the fibre content of the SFRC of the study and the results are analysed and compared with the fibre contents of the mix design. Finally, a methodology to control the rebound of fibres of the SFRC is proposed based on the inductive method.

3.1. Calibration of the inductive method

In order to calibrate the methodology, three cylindrical expanded polystyrene samples were used. Their dimensions were 100 mm for both, the diameter and the height, entailing a volume (V) equal to 785.40 cm^3. One of them is presented with a SFRC sample in Figure 3.a. Next, different amounts of fibre (10.02, 20.08 and 30.17 g) were placed in order to obtain their ΔL_T using the inductive method. Figure 3.b presents the relationship between the amount of fibres placed in the samples and their ΔL_T considering the V. As observed, the relationship is linear and shows good fit (R^2 = 0,997). Therefore, Equation 1 was used to estimate the fibre content of the samples using the inductive method ($C_{f,i}$).

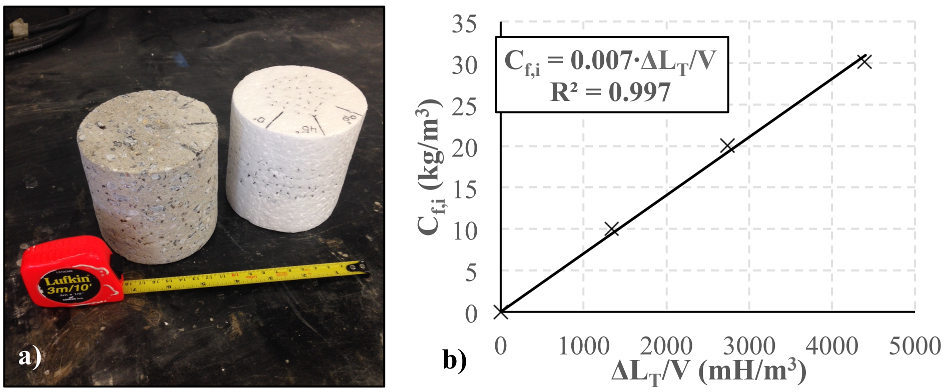

Figure 3- Cylindrical expanded polystyrene sample used to calibrate the method a) and calibration equation b)

$$C_{f,i}(kg/m^3) = 0.007 \cdot \frac{\Delta L_T(mH)}{V(m^3)} \quad (1)$$

3.2. Comparing between the inductive and the traditional method

To compare the methods one sample per each test panel was used. In that sense, their ΔL_T values were obtained using the inductive method and the estimated fibre content ($C_{f,i}$). Then, the samples were crushed in order to obtain the weight of fibres in them and their real fibre content ($C_{f,r}$) was calculated considering their volume (V). Figure 4.a shows a crushed sample and the magnet used to gather the fibres.

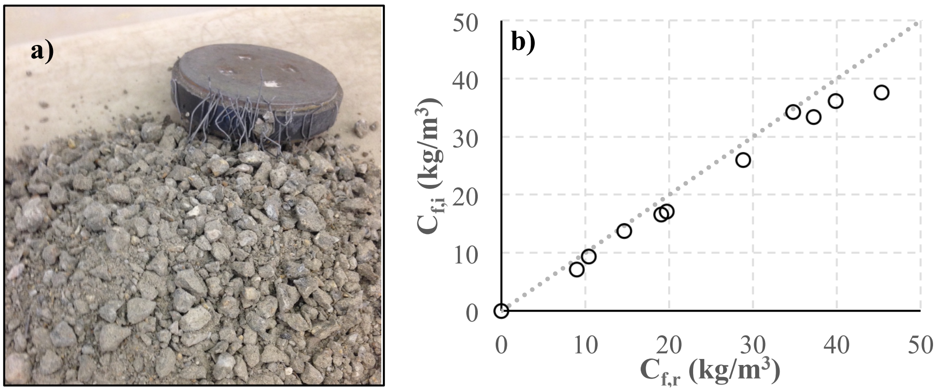

Figure 4- Traditional method a) and comparing between $C_{f,i}$ and $C_{f,r}$ b)

Table 2 presents the geometric parameters of the samples (h_m, ϕ_m and V), the weight of fibres obtained performing the traditional method (w_f), the values of ΔL_T from the inductive method and the real and estimated fibre content ($C_{f,i}$ and $C_{f,r}$, respectively). Notice that $C_{f,i}$ was calculated using the Equation 1 and $C_{f,r}$ was the results of dividing the w_f and the V of the samples.

Table 2- Results for comparing the methods

Dosage	Test panel	h_m (mm)	ϕ_m (mm)	V (cm^3)	w_f (g)	$C_{f,r}$ (kg/m^3)	ΔL_T (mH)	$C_{f,i}$ (kg/m^3)
1	1	106.89	99.71	834.53	7.54	9.04	0.85	7.13
	2	103.69	100.03	814.83	11.95	14.67	1.60	13.75
2	3	101.00	99.69	788.26	8.22	10.43	1.05	9.32
	4	102.07	99.99	801.50	15.32	19.11	1.90	16.59
3	5	107.38	99.74	838.94	31.25	37.25	4.00	33.38
	6	107.76	99.75	842.12	16.61	19.72	2.05	17.04
4	7	105.18	100.02	826.41	28.75	34.79	4.05	34.30
	8	94.76	99.85	741.94	21.44	28.90	2.75	25.95
5	9	106.46	99.76	832.09	33.18	39.88	4.30	36.17
	10	107.31	99.75	838.48	38.02	45.34	4.50	37.57

Considering the results obtained for the traditional and the inductive methods, an average difference of 11.32% is observed between $C_{f,r}$ and $C_{f,i}$ (Figure 4.b). This difference is possibly due to two factors: an error done during the gathering of the fibres of the traditional method and the precision of the inductive machine. Even though, the difference is not significant and, therefore, considering the advantages and drawbacks of the methods, the inductive method is more suitable for the control of the material than the traditional method.

3.3. Fibre content estimation of the SFRC

The inductive method was used to assess the fibre content ($C_{f,i}$) of the 50 samples using Equation 1. Table 3 presents these results by test panel and dosage. Therefore, the presented values are averages of 5 different results. The variance is also presented between brackets. Furthermore, the average of h_m, ϕ_m, V and ΔL_T are also shown with their respective variances. Finally, the table presents the different project fibre contents ($C_{f,p}$).

Table 3- Global results of the study

Dosage	Test panel	h_m (mm)	ϕ_m (mm)	V (cm^3)	ΔL_{TOT} (mH)	$C_{f,i}$ (kg/m^3)	$C_{f,p}$ (kg/m^3)
1	1	105.06 *(1.92%)*	99.72 *(0.07%)*	820.54 *(2.02%)*	1.20 *(20.20%)*	10.27 *(21.63%)*	20.00 -
	2	101.12 *(3.58%)*	99.85 *(0.14%)*	791.82 *(3.70%)*	1.36 *(13.61%)*	12.03 *(13.41%)*	20.00 -
2	3	103.95 *(1.88%)*	99.74 *(0.05%)*	812.17 *(1.94%)*	1.30 *(22.43%)*	11.18 *(21.41%)*	30.00 -
	4	100.65 *(5.92%)*	99.98 *(0.09%)*	790.16 *(5.97%)*	1.52 *(23.45%)*	13.41 *(21.01%)*	30.00 -
3	5	106.17 *(2.27%)*	99.86 *(0.11%)*	831.56 *(2.29%)*	2.93 *(26.43%)*	24.65 *(25.82%)*	35.00 -
	6	107.75 *(1.46%)*	99.91 *(0.28%)*	844.72 *(1.85%)*	2.09 *(4.60%)*	17.32 *(4.80%)*	35.00 -
4	7	97.37 *(6.32%)*	99.87 *(0.14%)*	762.74 *(6.36%)*	2.83 *(25.50%)*	25.78 *(19.80%)*	45.00 -
	8	96.58 *(5.02%)*	99.94 *(0.12%)*	757.62 *(4.99%)*	2.86 *(18.60%)*	26.35 *(14.88%)*	45.00 -
5	9	104.34 *(1.82%)*	99.90 *(0.15%)*	817.91 *(1.65%)*	3.71 *(18.34%)*	31.75 *(18.45%)*	55.00 -
	10	99.81 *(5.66%)*	99.83 *(0.06%)*	781.24 *(5.64%)*	3.99 *(12.29%)*	35.81 *(12.70%)*	55.00 -

The table presents a variation of the results considering same dosages and test panels. These variations are acceptable for SFRC [5, 8]. On the other hand, considering the values of $C_{f,i}$ and $C_{f,p}$ a tendency, presented in Figure 5, is observed (Equation 2). The relationship between $C_{f,p}$ and $C_{f,i}$ is linear and presents a good fit (R^2 = 0.869). The difference between this two parameters should be controlled as a decrease of fibre content leads to modify the post-cracking behaviour of the SFRC [2, 3, 4].

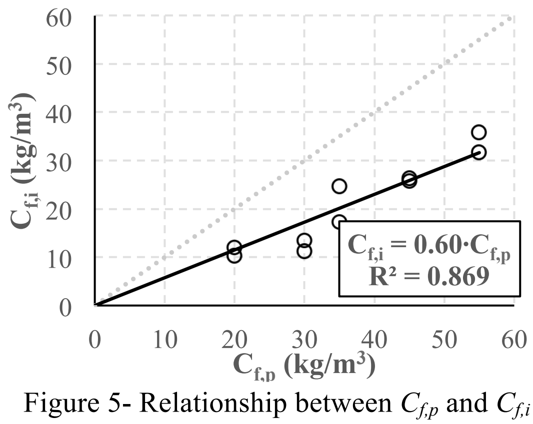

Figure 5- Relationship between $C_{f,p}$ and $C_{f,i}$

$$C_{f,i} = 0.60 \cdot C_{f,p} \tag{2}$$

The rebound is the phenomena that entais the difference between $C_{f,p}$ and $C_{f,i}$ [6]. In that sense, the slope parameter of the Equation 2 (m = 0.60) could be used to estimate the rebound of fibres during the spraying process (r) (Equation 3). For the studied SFRC, r is equal to 40%. Taken into account that the r values are between 30 and 50% [5, 6, 7, 13], r is admissible. Then, considering r and Equation 2 an analytical expression is presented so as to calculate the fibre content that should be sprayed ($C_{f,0}$) in order to obtain a final content of fibres ($C_{f,i}$) equal to the content of fibres considered in the project ($C_{f,p}$) Equation 4. In that sense, the aim of this equation is to avoid a worsening of the post-cracking behaviour of the SFRC considering the effect of the rebound.

$$r\ (\%) = 100 \cdot (1 - m) \quad (3)$$

$$C_{f,0} = (1 + r/100) \cdot C_{f,p} \quad (4)$$

3.4. Methodology of SFRC fibre content control

In order to control de fibre content of the placed SFRC and, therefore, verify that its amount of fibres ($C_{f,i}$) is at least the fibre content established in project ($C_{f,p}$), a preliminary and in-situ assessment need to be perform, as illustrated in Figure 6. The preliminary assessment consists of estimating the rebound of fibres (r) using the inductive method. In order to do that, test panels are sprayed considering different fibre contents ($C_{f,p}$) and samples are obtained from them regarding the requirements of the European standard UNE-EN 14488-2:2007. Next, the inductive method must be calibrated considering the type of fibre used. These are tested using the inductive method and $C_{f,i}$ are obtained. These are correlated with $C_{f,p}$ in order to calculate r using the Equation 3.

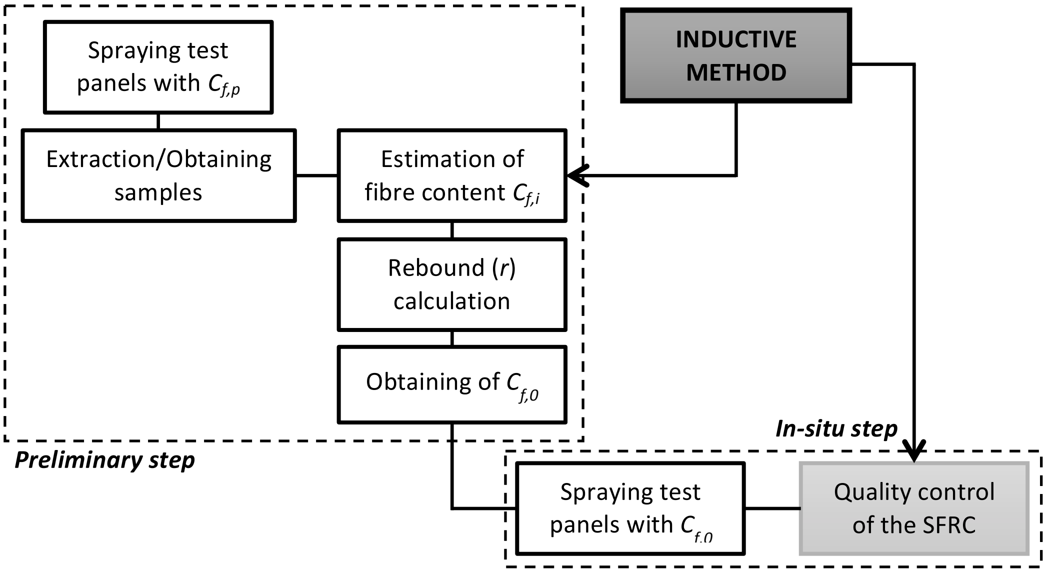

Figure 6- Methodology proposed to control the fibre content of a SFRC based on the inductive method

Subsequently, the fibre content that should be sprayed ($C_{f,0}$) in order to obtain a final amount of fibres ($C_{f,i}$) equal to the content of fibres considered in the project ($C_{f,p}$) is calculated considering Equation 4 and the former value of r. Finally, the inductive method is used to perform a quality control of the SFRC of the structure allowing the engineers to verify that the structure fulfil the post-cracking behaviour requirements specified in the project regarding the fibre content.

4. Conclusions

Based on the results and the analysis conducted, it is clear that the inductive method is an excellent tool to assess the fibre content of the SFRC. Furthermore, a methodology to control the rebound of fibres of the SFRC based on the inductive method is proposed. In addition, the following conclusions are drawn from the findings of this study:

- The inductive method eliminates the drawbacks of the traditional method: It is a non-destructive test that avoids the experimental errors (human factor). Furthermore, the inductive method reduces an 87% the time used to assess the quantity of fibres of sample facilitating performing a wider quality control of the material.

- The calibration of the inductive method is simple: making a correlation between a known fibre content per volume and the total inductive increment measured can be done considering the type of fibre used. In this study the traditional method was used to verify the calibration of the inductive method. The results show a difference of 11.32% between the real fibre content ($C_{f,r}$) obtained by means of the traditional method and the estimations ($C_{f,i}$) from the inductive method. This non-significant difference states that the inductive method can be used to estimate the fibre content of SFRC mixes avoiding the drawbacks of the traditional method.

- Using the inductive method the rebound of the fibre content of the SFRC can be estimated. In that sense, the rebound estimated for the SFRC of the study was 40%. Considering this and the type of the fibres used, the content of fibres than should be sprayed ($C_{f,0}$) in order to obtain a placed quantity of fibres ($C_{f,i}$) equal to the fibre content established in the project ($C_{f,p}$) can be determined. In order to do that, Equation 4 is presented in this study.

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